METHOD AND APPARATUS FOR ELECTRICALLY ADJUSTING

DELAY IN RADIO-FREQUENCY SYSTEMS

FIELD OF THE INVENTION

The present invention relates to adjustable radio-frequency delay elements. More
5 specifically, the present invention relates to apparatus for electrically adjusting delay in a radio-
frequency systems.

BACKGROUND OF THE INVENTION

Various radio-frequency systems, notably feed forward amplifiers and predistorters,
require the adjustment of delay through signal paths. This is typically done by varying lengths of
10 transmission line, tuning filters for group delay, adding fixed delay increments, or other
methods. All of these approaches require mechanical adjustment, circuit modifications, or other
operations that greatly complicate the manufacturing process and increase cost. There is a need
for a method to electrically adjust the delay in these applications without introducing
complications or impairments that render the approach unworkable.

15 ## SUMMARY OF THE INVENTION

According to one aspect of the invention, there is provided an electrically adjustable RF
delay element, including a splitter to split an input signal into two signal paths. One signal path
is delayed by a fixed integral number of wavelengths of a desired center frequency and both
signal paths are attenuated using electrically adjustable attenuation such that the sum of the
electrically adjustable attenuation provided by the signal paths adds to unity. A combiner then
combines the signals passing through the signal paths. The input signal is delayed by an
adjustable time depending upon the attenuations provided by the signal paths.

Preferably, a balanced variable attenuator provides the splitter and signal paths and an RF
delay element having a delay fixed at an integral number of wavelengths of a desired center
frequency. The fixed delay element is connected between port 3 of the balanced variable
attenuator and a first input of the combiner and a second input of the combiner is connected to
port 2 of the balanced variable attenuator, whereby an RF signal applied to port 1 of the balanced
variable attenuator is delayed by an adjustable time depending upon the degree of attenuation

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provided by the balanced variable attenuator and is provided at the output of the combiner.

Preferably, the balanced variable attenuator is formed from identical shunt-mounted reflective attenuators are connected between a pair of quadrature hybrid couplers or by identical series-mounted reflective attenuators are connected between a pair of quadrature hybrid couplers. Preferably, the reflective attenuators are PIN diodes.

According to another aspect of the invention, there is provided a method for providing an electrically adjustable delay of an RF signal. The method includes the steps of splitting the RF signal into two intermediate signals; delaying one intermediate signal by a fixed integral number of wavelengths of a desired center frequency; attenuating both intermediate signals by electrically-adjustable attenuation factors such that the sum of the attenuation factors is unity; and combining the intermediate signals into an output signal.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the present invention will now be described, by way of example only, with reference to the attached Figures, wherein:

Figure 1 is a block diagram of an electrically adjustable delay element in accordance with
5   an embodiment of the present invention;

Figure 2 is a block diagram of a conventional balanced attenuator using PIN diodes in a series configuration;

Figure 3 is a block diagram of a conventional balanced attenuator using PIN diodes in a shunt configuration;

10   Figure 4 is a block diagram of an electrically adjustable delay element in accordance with an embodiment of the present invention using PIN diodes in a series configuration;

Figure 5 is a block diagram of an electrically adjustable delay element in accordance with an embodiment of the present invention using PIN diodes in a shunt configuration;

DETAILED DESCRIPTION OF THE INVENTION

15   Delay is equal to the negative of the first derivative of phase with respect to time. As such, it should be realized that any approach used to adjust delay must not just adjust phase,

but actual delay.

In general, each embodiment of the invention uses two signal paths, one that has a fixed delay greater than the other by N/F_0 where N is an integer and F_0 is the center frequency of the intended system. The non-delayed path is multiplied by a scalar A that can

5   have a value from 0 to 1, and the delayed path is multiplied by a scalar equal to $(1 - A)$. The two products are then summed, and since the delay difference between them is equal to N wavelengths, they add in phase. The resulting delay of the combined signals is equal to zero when $A = 1$, and is equal to N/F_0 when $A = 0$. Between $A = 0$ and $A = 1$, the delay scales linearly. The useful bandwidth over which this relationship holds true is inversely proportional

10   to N. In practical application, the limit of N is about 4 for reasonable bandwidth.

Referring now specifically to Figure 1, an electrically adjustable RF delay element in accordance with an embodiment of the invention is indicated generally by reference numeral 10. The delay element 10 has an RF input port 12 and an RF output port 14. Two signal paths run from the RF input port 12 to the RF output port 14. An input signal received at the RF input port

15   12 is split by a splitter 16 into two paths which are recombined at a combiner 18 and feed to the RF output port 14. The first of the two paths includes a first attenuator 20 and the second path includes a second attenuator 22 and a fixed delay element 24. As mentioned above the two paths have delays that differ by N/F_0 seconds and the attenuators 20, 22 are adjustable so that the sum of their attenuations factors is constant.

20   A difficulty arises in attempting to multiply the delayed and non-delayed signals by A and $(1 - A)$. While it is possible to split an input signal, multiply the output signals with separate variable attenuators by A and $(1 - A)$, delay the second signal, and then recombine, there are problems with this approach. First, A and $(1 - A)$ are linear parameters which are difficult to accurately produce using conventional attenuators, which are typically linear in dB.

25   It is doubly difficult to produce A and a perfectly matching $(1 - A)$. Second, splitting the input signal in two and then later recombining yields a minimum insertion loss of 6 dB. It is desirable to keep the insertion loss as low as possible. Hence, while it is believed that an embodiment of the invention shown in Figure 1 using conventional attenuators can provide an electrically variable delay, the other embodiments described below in relation to Figures 4 and 5, which

30   utilize modifications of the conventional balanced variable attenuators depicted in Figures 2 and

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3, are preferable.

Figure 2 depicts a conventional balanced variable attenuator, generally indicated by reference numeral 30, in which identical series-mounted reflective attenuators 32, 34 are connected between an appropriately connected pair of quadrature hybrid couplers 36, 38.

5   Reflective attenuators 32, 34 are typically PIN diodes. The conventional balanced variable attenuator 30 has four ports, usually referred to as ports 1 to 4. Ports 1 and 3 are connected to one quadrature hybrid coupler 36, whereas ports 2 and 4 are connected to the other hybrid coupler 38. Port 1 is connected to an RF input 40, while port 2 is connected to an RF output 42. The port 3 and 4 are terminated with terminators 44, 46. If PIN diodes are used as attenuators

10   32, 34, then the attenuation between the RF input 40 and the RF output 42 may be controlled by varying the bias on the attenuators 32, 34 in a manner understood by those skilled in the art.

Similarly, Figure 3 depicts an alternative form of conventional balanced variable attenuator, generally indicated by reference numeral 50, in which identical shunt-mounted reflective attenuators 52, 54 are connected between an appropriately connected pair of

15   quadrature hybrid couplers 56, 58. Reflective attenuators 52, 54 are typically PIN diodes. The conventional balanced variable attenuator 50 has four ports, usually referred to as ports 1 to 4. Ports 1 and 3 are connected to one quadrature hybrid coupler 56, whereas ports 2 and 4 are connected to the other hybrid coupler 58. Port 1 is connected to an RF input 60, while port 2 is connected to an RF output 62. The port 3 and 4 are terminated with terminators 64, 66. If PIN

20   diodes are used as reflective attenuators 52, 54, then the attenuation between the RF input 60 and the RF output 62 may be controlled by varying the bias on the reflective attenuators 52, 54 in a manner understood by those skilled in the art.

The embodiments of the invention shown in Figures 4 and 5, are each a modification of one of the conventional balanced variable attenuators 30, 50 shown in Figures 2 and 3. As such,

25   the same reference numerals are used where appropriate.

In the electrically-adjustable RF delay elements indicated generally by reference numeral 70 in Figure 4 and reference numeral 80 in Figure 5, the termination 46, 66 connected to port 3 of the balanced variable attenuator 30, 50 has been replaced by a delay element 72 connecting port 3 of the balanced variable attenuator 30, 50 to an input of a combiner 74. The delay

30   element 72 provides a fixed delay of N / F_0, as discussed above, which means that the phase of a

signal passing through the delay element 72 is unaffected. Port 2 of the balanced attenuator 30, 50 is now connected to the other input of the combiner 74 and the output of the combiner 74 becomes the RF output 76 of the electrically-adjustable RF delay element 70, 80.

The delay provided by either form of electrically-adjustable RF delay element 70, 80 is

5   varied by adjusting the bias applied to the reflective attenuators 32, 34, 52, 54. If the voltage transfer characteristic from port 1 to port 2 of either form of electrically-adjustable RF delay element 70, 80 is S21 and the voltage transfer characteristic from port 1 to port 3 is S31, then $|S31| + |S21| = 1$. Therefore $|S31| = 1 - |S21|$, which is the characteristic needed to feed the non-delayed and delayed paths. Stated equivalently, if the attenuation from node 1 to node 2 is A,

10   then the attenuation from node 1 to node 3 must be $(1 - A)$, which is exactly what is needed. Further, the phases of the signals at the inputs of the combiner 74 are the same at −90 degrees. The combiner 74 is shown as an in-phase combiner although it is possible to use a quadrature combiner as long as the 90-degree phase difference is accounted for in the delay element 72.

This approach has two distinct advantages. First, scalars A and $(1 - A)$ are

15   accurately created by the action of the modified balanced attenuator. This would be very difficult to accomplish with a pair of attenuators. Second, the insertion loss of this approach is 3 dB, which is 3 dB less than the approach using two attenuators.

The above-described embodiments of the invention are intended to be examples of the present invention and alterations and modifications may be effected thereto by those of skill in

20   the art without departing from the scope of the invention that is defined solely by the claims appended hereto.